Cybersickness Between a Virtual and Mixed Reality Flight Simulator – A Comparative Study

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ABSTRACT

Cybersickness is a sickness-like phenomenon that occurs in virtual environments and when using head-mounted displays (HMD). Previous research has shown that virtual environments often induce cybersickness which can negatively impact students' training in simulators. Understanding and mitigating cybersickness are imperative for taking the next steps of ubiquitously adopting Extended Reality (XR) technology for training and education. A knowledge gap exists regarding the distinctions in cybersickness induced by different HMD technologies. Such as whether there is a difference in cybersickness severity between Mixed Reality (MR), where the environment is less virtual and more real, and Virtual Reality (VR), which presents a full-immersive virtual environment. This study aimed to compare cybersickness severity between MR and VR during a simulated flight scenario by using the video see-through HMD Varjo XR3. Twenty-nine subjects participated in the study and were administered the Simulator Sickness Questionnaire (SSQ) and the Fast Motion Sickness Scale (FMS). In conclusion, MR appears to induce slightly less severe cybersickness than VR, with disorientation symptoms being predominant in both environments.

This paper discusses symptoms of, methods to measure and quantify, and factors known to induce cybersickness. The choice of methods, design, and execution of the study along with a discussion on the results and their implications will be presented. Future work will investigate measurements of physiological and neurophysiological parameters aiming to identify the onset, intensity and type of cybersickness experienced.

ABOUT THE AUTHORS

Christian K. K. Lindberg is a researcher and developer at the Swedish Defence Research Agency (FOI). He served in the Swedish Armed Forces for a decade. Earned his BS in Computer and Systems Science, specializing in Game Development, from Stockholm University in 2021 and MS in Computer Science, specializing in Interactive Media Technology, from the Royal Institute of Technology KTH in 2023.

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Robert Ramberg PhD in cognitive psychology (1996) and professor at the Department of Computer- and Systems Sciences, Stockholm University. His research interests include learning, collaboration and training and more specifically how the design and use of technology, and other tools, can facilitate and strengthen such processes. Ramberg also holds a position as research director at FOI, doing research on flight simulation and training.

Guilherme Elçadi PhD is a distinguished scholar in rehabilitation medicine, currently holding a research position at the FOI. His extensive expertise is focused on the realms of brain activity and cognition. He specializes in employing advanced physiological measurements, including fNIRS, HRV, EEG, EMG, and more, to discern and elucidate pilots' cognitive and behavioral states. Furthermore, Dr. Elçadi is deeply engrossed in the field of evaluating fighter pilot training programs and exploring the immersive world of virtual reality scenarios.

Jouni Lindqvist is the technical director at FLSC, the SwAF Air Combat Simulation Centre. He has more than 30 years of experience as a software developer, research engineer and M&S expert within the areas of distributed simulation, visual simulation and serious gaming/game technology. He studied computer science at the Royal Institute of Technology KTH.

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INTRODUCTION

The Swedish Air Force Combat Simulation Centre (FLSC), a department at the Swedish Defense Research Agency (FOI), develops and hosts a flight combat simulation facility since 1998 (FOI, 2022) and is conducting a research and development program on how immersive extended reality technology can be used with their flight simulator. There are many potential benefits but also limitations for training pilots in an eXtended Reality (XR) flight simulator (Cross et al., 2023). An often-reported limitation is the occurrence of sickness effects, referred to as cybersickness, when using XR headsets (Cross et al., 2023; Kemeny et al., 2020; LaViola, 2000; NATO Science and Technology Office, 2021; K. Stanney et al., 2020). XR is an umbrella term for all technologies that extend the reality we experience which include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Severe sickness can have negative effects on a pilot's training, potentially leading to reduced user performance (Miguel-Alonso et al., 2023) or discourage pilots from using XR-based flight simulators altogether (Davis et al., 2014; NATO Science and Technology Office, 2021). Hence, it is imperative to investigate the anticipated severity of cybersickness and explore mitigation strategies before adopting this new technology extensively.

Head-Mounted Display (HMD), also known as headsets or goggles, a key XR technology for displaying virtual worlds in stereoscopy which have seen rapid development in the last two decades. There are two primary types of HMDs capable of displaying AR or MR experiences: Optical See-Through (OST) and Video See-Through (VST) HMDs (Jerald, 2015). Previous research has shown that OST HMDs can elicit severe cybersickness (Kaufeld et al., 2022), with the severity diminishing as the environment becomes less virtual and more real (Kirollos et al., 2022). Predominant symptoms associated with OST HMDs typically revolve around oculomotor discomfort (Hughes et al., 2020; Van Benthem et al., 2021). However, a notable gap in knowledge persists regarding the distinctions in cybersickness induced by different HMD technologies (NATO Science and Technology Office, 2021). As the technology becomes a more widely endorsed military training and operations tools, more investigations of cybersickness will be necessary to understand the limitations, capabilities, and potential use cases of headset technologies.

This research aims to provide valuable insights into the utilization of XR technology in flight simulation training and to inform potential strategies for alleviating cybersickness within this context, for the modeling and simulation community. Underscoring that cybersickness can negatively impact students' training, understanding and mitigating cybersickness are imperative for taking the next steps of ubiquitously adopting XR technology for training and education in the field of modeling and simulation.

The primary objective of this study was to evaluate the differences in cybersickness experienced during flight simulation in a VR versus MR environment using a video see-through head-mounted display. Specifically, the aim was to test the hypothesis that cybersickness will be less severe in the MR flight simulator compared to the VR flight simulator.

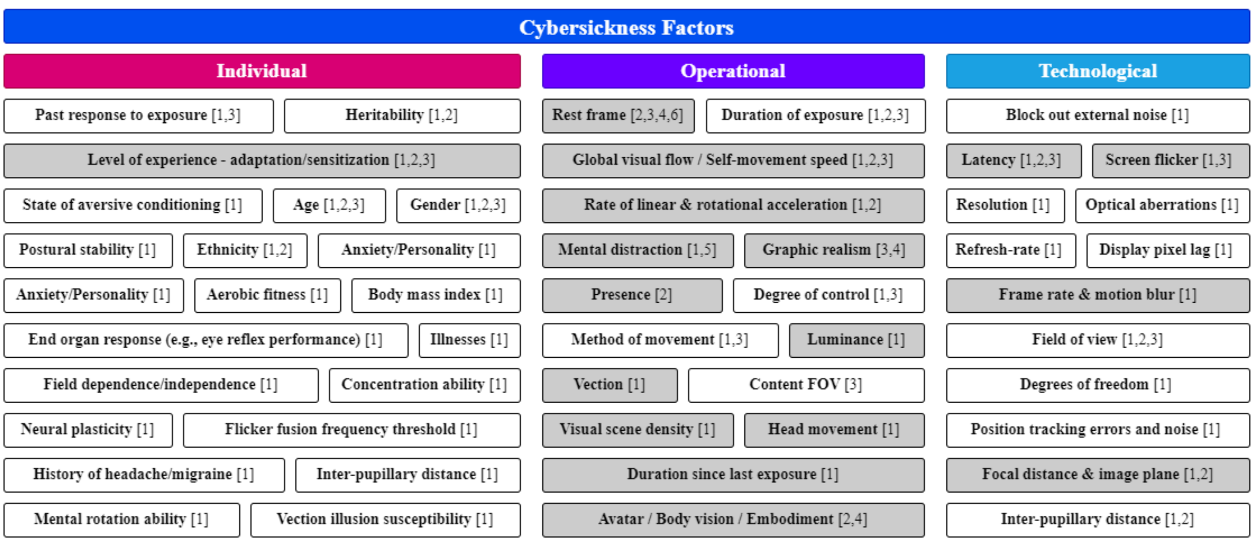
SYMPTOMS AND MEASUREMENTS

A detailed symptom review, conducted by Bos and Lawson (2021), revealed a total of 34 symptoms, with 24 categorized as "well-established" – such as disorientation, headache, nausea, and eyestrain. Some symptoms are psychological relying on introspection to be measured, thus highly subjective, while others can be objectively observed through behavior or physiological responses. Certain symptoms, such as nausea, straddle the line between psychological and neurophysiological domains. Self-report questionnaires have been the main tool for measuring cybersickness, with the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) standing out as the most well-known and widely used. While alternative self-report questionnaires focusing on visually induced sickness exists (H. K. Kim et al., 2018; Stone III, 2017), they are less validated than the SSQ (Bos & Lawson, 2021; Kemeny et al., 2020). For this study, the SSQ was chosen due to its established usage and ease of cross-study comparison. The SSQ can differentiate symptoms in three dimensions: nausea, disorientation, and oculomotor discomfort.

Furthermore, to facilitate swift assessment of cybersickness progression during experiments, single-answer self-report measures have been developed. The Fast Motion Sickness scale (FMS), devised and validated against the SSQ by Keshavarz and Hecht (2011), prompts subjects to rate their sickness on a scale from 0 (no sickness) to 20 (severe sickness). Other alternatives exist (Bos et al., 2005; Kaufeld et al., 2022) which may not be as widely used or necessitate subjects to familiarize themselves with a non-intuitive rating scale in advance, which influenced the choice of the FMS for this study.

CAUSE OF CYBERSICKNESS

Currently, there is no universally accepted theory or solution that fully explains and mitigates motion sickness and its subsets. The widely embraced 'Sensory Conflict theory', initially outlined by Reason and Brand in 1975 (Reason & Brand, 1975), posits that motion sickness arises due to a discord between current sensory information and the brain's expectations based on prior experiences. Although there is no consensus on why cybersickness occurs, there are many known factors of influence. As part of the current study, a mind-map of factors mentioned in literature was created, shown in Figure 1, but should not be seen as exhaustive. We refer the avid reader to their respective references in the figure. The factors are divided into three categories: individual, technological, and operational. A review of how these factors may change between our two simulator exposures revealed that 17 factors could have an influence. These are highlighted gray in Figure 1.



[1] = (B. D. Lawson et al., 2021); [2] = (Kemeny et al., 2020); [3] = (Chang et al., 2020); [4] = (Leoncini et al., 2021); [5] = (Bos & Lawson, 2021); [6] = (Prothero, 1998)

Figure 1. Three Categories of Potential Factors Impacting Cybersickness

DIFFERING SEVERITY AND SYMPTOM PROFILES OF CYBERSICKNESS

The SSQ consists of 16 items, representing several symptoms, and the instrument outputs a Total Score (TS) and three subscale scores: Oculomotor discomfort (O), Disorientation (D), and Nausea (N) that are used to build symptom profiles to characterize an exposure. Stanney and Kennedy (1997) pointed out that sickness in VR with HMDs was more severe than the previously studied simulator sickness and showed that the sickness effect from HMDs, cybersickness, seemed to have an SSQ symptom profile of D>N>O with an SSQ-TS averaging above 20. In a subsequent paper, they made the argument that cybersickness should be distinguished from simulator sickness (K. M.

Stanney et al., 1997). More recently, the predominance of disorientation symptoms in VR was confirmed in a systematic review (Saredakis et al., 2020).

Less research has been done on characterizing cybersickness in various virtuality levels of MR. So far, research has focused on AR with OST HMDs and findings show that symptoms of oculomotor discomfort are predominant (Kaufeld et al., 2022; Van Benthem et al., 2021) and that sickness effects are generally less severe when compared to VST HMDs in VR (Van Benthem et al., 2021). In addition, recent findings suggests that fewer virtual objects in MR correlate with less severe cybersickness (Kirollos et al., 2022).

In their book, Kemeny et al. (2020) explained that OST HMDs elicit lower cybersickness effects compared to VST for several reasons: they keep external visual references visible - giving a stable world reference, the real-world visuals suffer no latency, and they lead to less vergence-accommodation conflict of the eyes. The first reason could be achieved in a VST HMD, as well, by showing more of the real-world environment. Thereby mitigating cybersickness by providing the brain with a clearer earth-fixed rest frame, following the "rest frame hypothesis" introduced in the previous section. What we see is a knowledge gap in how cybersickness compares in various levels of virtuality using a VST HMD. A technology that in the last few years has shown great advances in displaying MR environments.

DESIGNING THE SIMULATOR SCENARIO

Lawson and Stanney (2021) pointed out that one should use stimuli that elicit functionally relevant cybersickness when conducting research in the field. Meaning that the exposure should be provocative enough to elicit sickness, or nothing can be measured, while still not being too provocative or the subject may abort the test. Furthermore, researchers recommend the duration of exposure to be at least 20 minutes when peak sickness is often reached (Caserman et al., 2021; J. Kim & Park, 2020). The current study also aimed to design a flight scenario that is close to a real-world context of how pilots may operate a flight simulator.

With the above in mind, the following simulator scenario[1] was designed. Take off on a runway in Innsbruk, Austria. Climb and manually maintain an altitude of 4000 meter above sea level throughout a 30-minute session while flying towards a fixed set of checkpoints around western Austria. The area was chosen for its varying terrain height, resulting in varying visual flows at an altitude just above the mountains. The current altitude, and other flight data, was displayed on the Head-Down Display (HDD). The checkpoints were large pink balls in the terrain, which often could not be directly observed and, thus, needed to be located on a map in the HDD. The pink ball had an alphabetic letter on top of it, which needed to be spoken aloud to get the next checkpoint. Once every minute, a question was to be attended on the HDD, which asked how sick the subject was feeling (this is the FMS measure). These tasks of maintaining the correct altitude, locate and fly towards a checkpoint, observing the letters on the checkpoints, and rate felt sickness on the HDD, aimed to keep the subject's gaze alternating between the HDD and the terrain, to keep the subject cognitively engaged, and lead to a functionally relevant cybersickness.

METHOD

Subjects

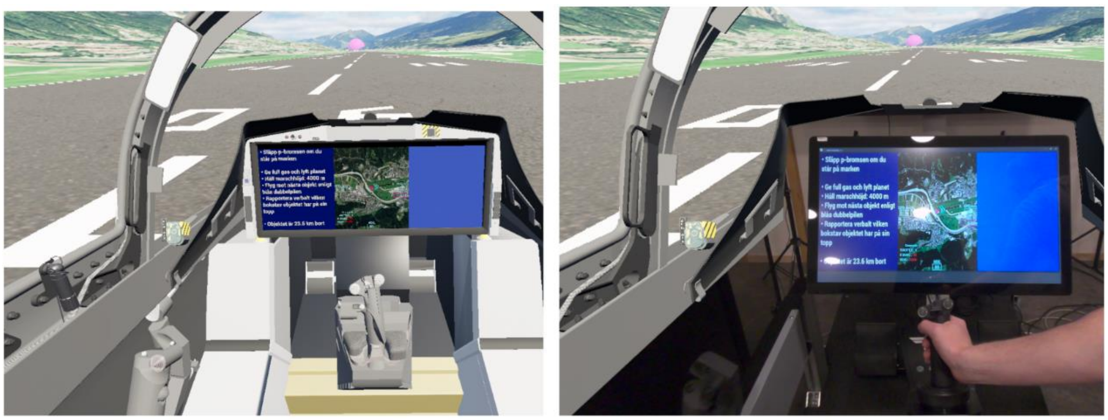
Twenty-nine volunteers, 28 males and 1 female, ages ranging from 23 to 62 years (M = 40, SD = 12) participated in the present study. All subjects were in good health and had no reported issues with their vestibular sensory system. Some subjects wore eyeglasses during the test protocol, and five subjects did not wear glasses although they had minor vision disorders. All subjects finished the test protocol and none terminated their session before the end of the protocol. Prior to testing, subjects were asked about their general health and none reported any chronic medical condition that required any kind of regular medication. Subjects signed informed consents prior to the participation in the study and were given verbal and written descriptions of the experiment protocols.

Material

A flight simulator was developed for the Varjo XR-3 headset (Varjo, Helsinki, Finland) using the Unreal Engine 5.1 (Epic Games, Cary, NC, USA). For simulating flight dynamics, the JSBSim 1.1.13 (JSBSim, Open Source) was used,

[1] Video exemplifying the flight scenario is available here: https://www.youtube.com/watch?v=rNgK-zp53o0

and Cesium plugin (Cesium GS, Philadelphia, PA, USA) was used for terrain generation of the real world. For the present study a simple 3D model of a SAAB JAS 39 Gripen fighter jet was given the flight dynamics of a General Dynamics F16/A Fighting Falcon, included with the JSBSim plugin. In VR, all the instruments and switches in the cockpit were removed, except for a virtual display in front of the subject with flight data and flight instructions. In MR, a video see-through camera, using Varjo's stencil masking technique replaced the cockpit. The setup allowed for a real-world digital display and the view of the real-world surrounding area (see Figure 2). A Windows 10 computer with, Nvidia GTX 3080 (Nvidia Corporation, Santa Clara, CA, USA), 3200 MHz DDR4 RAM, and 10th generation Intel i7 (Intel Corporation, Santa Clara, CA, USA) ran the simulator and powered the HMD Varjo XR-3 with Varjo Base 3.10 software. Four Steam VR base stations 2.0 (Valve Corporation, Bellevue, WA, USA) were used to track the HMD. To increase performance, the focal displays were turned off and resolution lowered to 1444 x 1236 with 33 pixels per degree, inside Varjo Base. The average frame rate during simulation was 36 frames per second.



(a) Virtual Reality **(b) Mixed Reality**

Figure 2. Comparison of the Two Virtuality Levels in the Developed Flight Simulator

Experiment Set-Up and Protocol

The experiment design used was to measure exposure differences through within-subjects testing of the two flight simulator exposures. The independent variable was the VR and MR cockpit environment. The dependent variable was cybersickness, indexed with SSQ and FMS. Adaptation/sensitization was a control variable. The experiment was conducted over a period of four weeks. Subjects attended the experimental laboratory individually on two occasions – one MR and one VR – with at least one day of recovery between occasions. The occasions were counterbalanced so that half of the subjects began with MR and the other half with VR, with the first subject being randomly assigned.

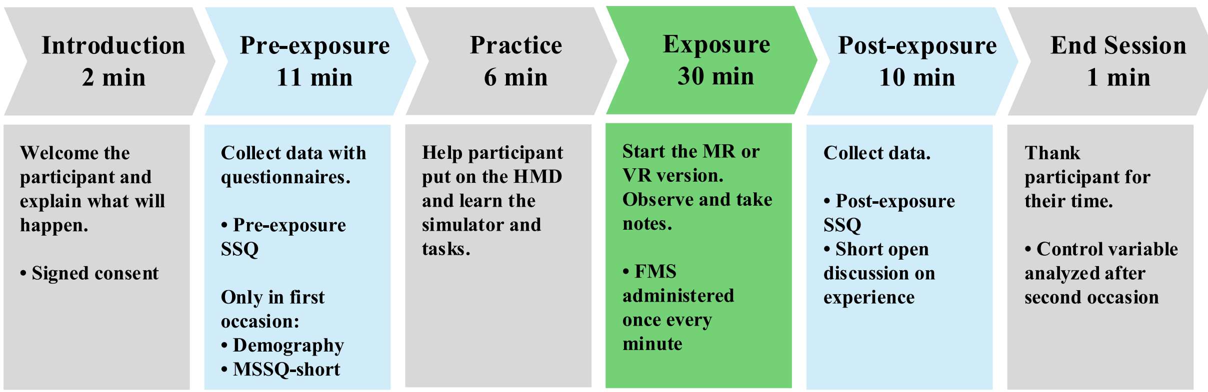
On the first occasion, subjects completed a demographic questionnaire and the short-form Motion Sickness Susceptibility Questionnaire. On both VR and MR occasions, subjects completed the SSQ followed by a brief instruction and a short practice session on how to operate the simulator. Thereafter, the simulator was rebooted, and the subject was instructed to put on headphones reproducing the sound of jet engines and wind noise, marking the beginning of the 30-minute flight exposure. The FMS was administered inside the simulator once per minute. The experimenter sat next to the simulator, observed the simulator on a display, and took notes. Immediately after the end of each flight, subjects answered the post-exposure SSQ and then discussed their experience. Each occasion lasted ~ 60 minutes. See Figure 3, below, for an overview.

Demographic Questionnaire and Motion Sickness Susceptibility Questionnaire

Demographic questionnaire and the short-form Motion Sickness Susceptibility Questionnaire (MSSQ-short) were administered on the first occasion. The MSSQ-short has 18 items designed to measure previous experiences of motion sickness rated on a 4-point Likert scale (Golding, 1998, 2006). An equation is then used to assess a total score of 0 to 54. A higher score indicates greater levels of susceptibility to motion sickness.

Simulator Sickness Questionnaire (SSQ) and Fast Motion Sickness Scale (FMS)

A pre-and post-exposure SSQ were administered on both occasions. The SSQ consists of 16 items, representing several symptoms, rated on a four-point Likert scale (Kennedy et al., 1993). The total score and three subscale scores, representing symptom categories, were derived from the questionnaire following equations of Bimberg et al. (2020). During exposure, FMS was administered inside the simulator once per minute, with responses saved in a CSV-file. The FMS asks the subject to rate their sickness from 0 (no sickness) to 20 (frank sickness).



Simulator Sickness Questionnaire (SSQ), Motion Sickness Susceptibility Questionnaire (MSSQ), Fast Motion Sickness scale (FMS), Virtual Reality (VR), Mixed Reality (MR)

Figure 3. Experiment Protocol Overview

Data Processing and Statistical Analysis

The SSQ scores were computed for each subject and their pre-exposure measurement was subtracted from their post-exposure. This resulted in a few negative values which could be interpreted as the exposure having a positive effect on the subjects. However, following a reasoning by Bimberg et al. (2020), negative scores were turned into zeroes, meaning the exposure is seen as having a no-negative instead of a positive effect on the subjects, resulting in the final SSQ scores. The SSQ scores and FMS ratings were imported into SPSS 28.0 for statistical analyses.

Data were explored for outliers and normality, revealing no extreme outliers and visual inspection of histograms and Shapiro-Wilk tests revealing that all data was non-uniform. For testing differences of means, Wilcoxon Signed Rank Test (WSRT) was used because this is a non-parametric statistical test that can be used for within-subjects, i.e., paired samples or repeated measure, data (Merchant & Kirollos, 2022). Effect sizes for significant results of WSRT were calculated with the formula $r = z/\sqrt{(n_x + n_y)}$, as explained by Pallant (2007), and interpreted following Cohen's (1988) criteria of 0.1 = small effect, 0.3 = medium effect, 0.5 = large effect. All results were interpreted on a significance level of $p = 0.05$.

RESULTS

Motion Sickness Susceptibility Questionnaire and Demography

The result of the MSSQ showed that the subjects could be seen as less susceptible to cybersickness, with a lower MSSQ-short score (M = 11.1, SD = 8.1) compared to a benchmark (M = 12.9, SD = 9.9) of Golding (2006). Furthermore, the demographic questionnaire probed the subjects' previous experience with flying aircrafts, flight simulators, and playing video games, on a scale of no experience (0) to a lot of experience (3). Results showed that the subjects had moderate experience in using flight simulators (M = 1.8, SD = 0.9), close to no experience in flying real aircrafts (M = 0.4, SD = 0.8), and moderate experience in playing video games (M = 2.2, SD = 0.8).

Simulator Sickness Questionnaire

Table 1 (see below) contains descriptive statistics of the SSQ scores, compared between VR and MR, and WSRT on differences of means. Shown is that the SSQ-TS mean was higher in the VR (M = 15.6, SD = 18.5) compared to the

MR (M = 12.6, SD = 13.8). This indicates that the cybersickness was slightly less severe in MR. WSRT was performed revealing that the difference in SSQ-TS between VR vs. MR was not statistically significant, z(29) = -0.78, $p = 0.44$.

Also shown in Table 1, the subscale ordering for VR was D>N>O (20.2 > 12.5 > 12.3) and for MR it was D>O>N (19.7 > 10.7 > 8.2). In both MR and VR, the subscale D scored higher than the other subscales, indicating that disorientation symptoms were predominant in MR and VR. The difference between D and the other subscales were tested with WSRTs (see results in Table 1), revealing that only for D vs. N in MR was D significantly higher, z(29) = -2.54, $p = 0.011$, with a moderate effect size ($r = 0.33$). Indicating that disorientation was more predominant than nausea in MR. Testing each subscale score between VR and MR with WSRT revealed no significant difference.

Table 1. Simulator Sickness Questionnaire scores and Wilcoxon Signed Rank Tests results

	Virtual Reality				**Mixed Reality**			
	TS	**N**	**O**	**D**	**TS**	**N**	**O**	**D**
	Pre-exposure SSQ scores							
Mean	10.8	6.6	11.0	10.6	8.6	5.6	10.0	5.8
Median	3.7	0.0	0.0	0.0	3.7	0.0	7.6	0.0
SD	13.5	19.7	19.7	23.7	11.6	13.1	14.8	18.8
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	44.9	66.8	91.0	97.4	52.4	66.8	60.6	97.4
	Post-exposure SSQ scores							
Mean	25.0	18.1	20.9	28.3	20.2	11.2	19.3	23.5
Median	18.7	9.5	15.2	13.9	18.7	0.0	15.2	13.9
SD	21.5	20.5	24.6	35.8	15.6	17.5	21.6	27.6
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	74.8	66.8	83.4	125.3	52.4	76.3	75.8	111.4
	Final SSQ scores							
Mean	15.6	12.5	12.3	20.2	12.6	8.2	10.7	19.7
Median	11.2	9.5	0.0	13.9	11.2	0.0	0.0	13.9
SD	18.5	16.7	20.1	33.4	13.8	16.5	18.6	27.2
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	71.1	57.2	75.8	125.3	44.9	76.3	75.8	111.4

	Wilcoxon Signed Rank Tests (z)			
	Virtual Reality		**Mixed Reality**	
	D vs. N	**D vs. O**	**D vs. N**	**D vs. O**
z(29)	-1.16	-0.92	-2.54	-1.72
p	0.25	0.34	0.01 ($r = 0.33$)	0.09
	Virtual Reality vs. Mixed reality			
	TS	**N**	**O**	**D**
z(29)	-0.78	-1.50	-0.67	-0.36
p	0.44	0.13	0.51	0.72

SSQ (Simulator Sickness Questionnaire), TS (Total Score), N (Nausea), O (Oculomotor discomfort), D (Discomfort), SD (Standard Deviation), r (effect size)

Fast Motion Sickness Scale

A WSRT, z(29) = -2.11, $p = 0.035$, showed that the mean FMS in VR (M = 1.34, SD = 2.04, N = 872) was significantly higher than in MR (M = 0.83, SD = 1.35, N = 867), with a small effect size ($r = 0.28$). This indicates that cybersickness was less severe in MR, which supports our hypothesis.

Correlation Analysis between MSSQ-Short and SSQ-TS

Correlation analysis was conducted to confirm that the MSSQ-short has a predictive power on cybersickness. With the data being non-uniform, the non-parametric Spearman's correlation test was performed and revealed that there was a strong positive correlation between the MSSQ score and SSQ-TS score in both VR, r(29) = 0.59, $p < 0.001$, and MR, r(29) = 0.59, $p < 0.001$.

Cross-Occasion Adaptation/Sensitization

Analyses were conducted to compare cybersickness between the occasions to assess if the subjects may have become adapted or sensitized to the exposure from their first (O1) to second occasion (O2). The SSQ-TS showed an increase from O1 (M = 13.3, SD = 16.7) to O2 (M = 15.0, SD = 16.1) and a WSRT revealed that it was not a significant difference, z(29) = -0.86, $p = 0.39$). The FMS mean showed a decrease from O1 (M = 1.13, SD = 1.78) to O2 (M = 1.05, SD = 1.72) and a WSRT revealed that it was not a significant difference, z(29) = -0.56, $p = 0.57$. Thus, no confounding factor affected the subjects between first to second occasions.

DISCUSSION

The primary objective of this study was to determine any differences in elicited cybersickness between a Virtual Reality (VR) and Mixed Reality (MR) flight simulator using a Video See-Through (VST) Head-Mounted Display (HMD). Based on previous research, the hypothesis was that *cybersickness will be less severe in the MR flight simulator compared to the VR flight simulator*. A VR and MR flight simulator was developed and used for testing exposure differences following a within-subjects experimental design. The dependent variable being cybersickness, indexed with the Simulator Sickness Questionnaire (SSQ) and the Fast Motion Sickness scale (FMS). Statistical analyses were conducted to evaluate the hypothesis.

The Severity of Cybersickness VR vs. MR

In our study, the mean SSQ-Total Score (TS) indicated less severe cybersickness in the MR flight simulator, although it did not achieve statistical significance. However, the mean ratings from the FMS showed a statistically lower score in the MR simulator, suggesting less severe cybersickness being elicited in MR. Taken collectively, these outcomes lend support to our first hypothesis. Nonetheless, further investigation is necessary to extend these findings to a broader population and the broader context of MR. This discovery aligns with prior research, which underscored the anticipation of a less severe cybersickness in MR scenarios utilizing Optical See-Through (OST) HMDs (Hughes et al., 2020; Kemeny et al., 2020; Van Benthem et al., 2021) and less severe cybersickness in MR scenarios with less virtual objects (Kirollos et al., 2022).

The Predominant Symptoms

The SSQ subscales in the current study showed that the Disorientation (D) symptoms scored higher than the other two symptom categories of Oculomotor discomfort (O) and Nausea (N) in both MR and VR. However, only in MR did we see a significantly higher D-score compared to N. In previous reports, oculomotor discomfort symptoms have generally been predominant with OST HMDs in AR (Hughes et al., 2020; Van Benthem et al., 2021). While disorientation has shown to be predominant in VR (Saredakis et al., 2020; K. M. Stanney et al., 1997) which occludes the real world like our HMD. More research is needed to confirm whether the predominant symptoms elicited in MR, by a VST HMD, are disorientation symptoms. However, we recommend that researchers distinguish between OST and VST when conducting research on cybersickness in MR.

What Influenced the Outcome of Severity in Cybersickness?

We knew of 17 factors that could influence the cybersickness between the two flight simulators. The current study can rule out the influence of adaptation or sensitization to cybersickness from the first to second occasion, the factor named “level of experience” in Figure 1. This cross-occasion adaptation/sensitization was investigated by comparing the SSQ-TS and FMS between the first and second occasion, which did not show a significant difference. The influence of any other factor cannot be ruled out, leaving us with 16 factors that could have influenced cybersickness in the current study.

Nevertheless, an interesting note is that when asked to talk about their experiences, two subjects explicitly stated that they felt the real world seen in MR gave a more stable frame of reference. Which relates to the rest frame hypothesis formulated by Prothero (1998) and is one of the operational factors. Parker and Prothero (2003) posited that it may be possible to reduce the sickness of a simulator if the user’s brain selects a visual background, a frame of reference, that agrees with the felt motion. In the current study, our subjects were not exerted to any physical motion. It could then be that having a view of a real-world cockpit, in MR, is more congruent with the lack of felt physical motion resulting in reduced sickness. Aligning with prior research showing that earth-referenced rest frames can help mitigate cybersickness (Cao et al., 2018). However, more research is needed to confirm that a better rest frame was the reason why our study saw less severe cybersickness in MR.

Another notable difference between our flight simulators is the lack of an own-body representation in VR, named “avatar/body vision/embodiment” in Figure 1. In their book, Kemeny et al. (2020) point out that research indicates a reduction of sickness effects when having own-body vision or a virtual own-body avatar representation, and a sense of embodiment. Since, in the current study, the subjects saw their own body in MR this could have had a mitigating effect on cybersickness. However, more research is needed to confirm this as well.

Limitations and Future Work

The current study's sample size could be perceived as relatively modest. Nevertheless, it is worth noting that our sample size of 29 falls within the range suggested by Caserman et al. (2021) (15 subjects) and Lawson and Stanney (2021) (70 subjects). However, we acknowledge that future research might yield more robust results by employing a larger sample size. In addition, our study could not control for all known cybersickness confounding factors. Future research should continue to investigate which factors have the largest impact on cybersickness. Of note, own-body representation and the role of rest frames in MR on mitigating cybersickness.

Our future work aims to assess cybersickness onset, intensity, and type of symptom based on SSQ results in fighter pilots during operational-like training scenarios, incorporating physiological and neurophysiological measurements. Additionally, we will compare pilot performance and cybersickness between XR headsets and traditional visualization technologies, i.e., dome projection and flat panel systems. Measuring bio-signals in response to psychological states is an active research area that could allow for more “objective” and real-time measuring of, e.g., cybersickness, mental workload, or stress, which in turn could be used for adapting training scenarios to a student’s zone of proximal development (Vygotsky & Cole, 1978), thus improving the learning process. Although our studies are based on the SSQ derived symptoms of D, O, and N we may consider in the future to include the Motion Sickness Assessment Questionnaire (Gianaros et al., 2001) which differentiate symptoms in four other dimensions, possibly increasing the spectrum of cybersickness quantification.

CONCLUSION

Utilizing a video see-through head-mounted display, less severe cybersickness seems to be expected in MR when compared to a VR flight simulator, with disorientation symptoms seemingly being predominant in both environments. However, it is important to emphasize that the findings from our study may not necessarily generalize broadly. We believe there are five important constituents to be aware of: (i) the aircraft steering was user-controlled; (ii) the video see-through head-mounted display Varjo XR-3 was utilized; (iii) in MR the user’s own body was seen through a video see-through part of the real world, whereas VR presented no own-body representation; (iv) the user only interacted with a physical throttle and stick; and (v) the sample was predominantly male, averaging 40 years of age with moderate experience of using flight simulators.

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